White Paper

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Digital Image Correlation to Determine Shape Deformation of Paper Based Collections Due to Relative Humidity and Temperature Variation

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The Image Permanence Institute (IPI) in the College of Art and Design at the Rochester Institute of Technology was awarded funding from the U.S. National Endowment for the Humanities (NEH) in 2015 to study the mechanical response of library and archive materials to changes in relative humidity (RH). This paper summarizes the findings of this research. A more detailed Final Activity Report was submitted to the NEH.

Previous IPI research investigating new methodologies for sustainable management of collection environments (NEH Grant # PR-50087-10) found that paper-based collections in typical storage configurations, as well as bound volumes, can take up to one month to reach full moisture equilibration with a sustained change in ambient RH. That research confirmed that collections do not fully "feel" short-term changes in RH affirming the potential for dynamic preservation environmental management and the implementation of sustainable HVAC operations in collections environments. While an entire, unenclosed object is slow to equilibrate, that study acknowledged "major differences exist between the 'skin' of an object and its core. In reality, the outside of an object always feels to some degree the effect of ambient RH cycling, while internally the object feels very little change." The project led to more questions about the physical response of collections materials to changes in the environment. Of particular concerns were bound volumes as they are complex composite structures made from a variety of hygroscopic materials all of which likely respond to changes in RH differently, resulting in the potential for mechanical deformation.

With a change in ambient RH, moisture diffuses into or out of hygroscopic objects from the outside-in. The binding of a book, or an object on top of a stack in a box, experience a change in moisture content first. When the moisture content changes, these objects physically respond by expanding with a gain in moisture or contracting with a loss of moisture. Excessive changes in moisture content can lead to permanent physical, or mechanical, damage to collections objects. As a result, storage recommendations for rare books have emphasized close control around a target of 45-55% RH to try and minimize risk of mechanical damage. What was not well established from actual experimentation, however, are the practical limits where irreversible damage takes place due to changes in RH. The objectives of this project were to characterize the mechanical behavior of paper-based collection objects, with a focus on bound volumes, in response to RH changes in order to define the safe limits of RH in regards to physical damage and better inform the environmental management policies used by libraries and archives.

Digital Image Correlation (DIC), a photogrammetry system for measuring mechanical deformation of an object's surface, was used to assess the mechanical response of various materials. While designed for industry, this system has been used in the arts to dynamically assess expansion and contraction of paintings and tapestries. The DIC system used by IPI requires two digital cameras positioned perpendicular to the test samples. The system also requires samples have a random, high contrast speckle pattern. The cameras and samples were placed in a temperature and humidity controlled walk-in chamber. The cameras captured images in stereo at regular intervals as the ambient RH changed. The images were then uploaded to software that tracks the movement of the speckles on the samples in three-dimensions and uses algorithms to calculate in-plane and out-of-plane displacement as well as the strain for the material tested. Data was produced as numerical data that can be graphed as well as visual 2-D and 3-D maps that can be animated. Prior to the introduction of DIC, cultural heritage research used tensile tests to characterize the mechanical behavior of materials. Tensile tests involve applying a known amount of stress to a two-dimensional object and measuring the resulting strain. Strain (ε) is a unit of deformation, usually expressed as a percentage. It is the ratio of change in length (ΔL) of a material to its original length (L) due to stress-induced extension or compression; $\varepsilon = \Delta L/L \times 100$ gives percent strain. From these two measurements, stress and strain, it is possible to determine the elastic limits and yield point of materials tested. The yield point is the stress at which a material begins to deform permanently. Prior to the yield point the material will deform elastically and will return to its original shape when the applied stress is removed. DIC only measures displacement and strain. However, the advantage of DIC over tensile testing is that it is possible to test completely unrestrained materials and to measure actual strain in three-dimensional structures, such as books. With DIC, IPI was able to make accurate measurements on the extent of expansion and contraction of materials tested in response to changes in RH, known as hygric strain. In addition, valuable information was gathered on the relationships between changes in RH, strain, and moisture content.

The laboratory research was divided into three parts: 1) a moisture equilibration study, 2) strain measurements using DIC with a single 20% change in RH at varying set points, and 3) strain measurements using DIC with multiple change in RH. Test samples included a range of single sheet materials from which books are made, such as paper, leather, cloth, and parchment as well as books bound with a variety of materials.

The purpose of part 1, the moisture equilibration study, was to collect accurate data on moisture equilibration rates of the single sheet sample materials in order to design testing profiles for the DIC studies. This study alone yielded some interesting results. Moisture equilibration was determined gravimetrically at the uppermost and lowermost RH limits of the walk-in testing chamber. A selection of single sheet samples were equilibrated to dry conditions of 10% RH and 20ºC, sealed individually in vapor-proof bags, and the chamber set point was increased to 80% RH. Each sample was placed on a balance and allowed to equilibrate to the more humid 80% RH environment, gaining weight as moisture diffused into the sample for twenty-four. The samples remained in the chamber until all samples had equilibrated, one at a time. The sample were weighed again, re-sealed in vapor-proof bags, the chamber set point was set to 10% RH and the testing procedure was repeated. When the sample were weighed again, each sample had gained at least a quarter to a third percent more water weight after the initial twenty-four hour equilibration period. It was determined it may take up to five days for some materials to reach full moisture equilibration at 80% RH and 20ºC. This material behavior may be explained in part by studying the sorption isotherm for cotton cellulose, which shows there is a dramatic increase in moisture content starting at 80% RH. A study on water vapor sorption of parchment published in 2016 in the Journal of Cultural Heritage also demonstrated a dramatic increase in moisture content at 80% RH in the sorption isotherm for parchment (Popescu 2016, 89). Conditions of 70% RH or higher are not recommended for hygroscopic collection objects like paper because excess water present can participate in chemical reactions and the growth of microorganisms.

In part 2, strain measurements using DIC looked at strain in single sheets of materials resulting from a single, 20% change in RH starting at different set points with four different testing profiles: two absorption and two desorption (see Table 1). All tests were conducted at a constant temperature of 20ºC. Tests in part 3 were designed to observe the mechanical behavior of both single sheet sample materials and books as the RH changed from 50% RH at 20ºC to a higher or lower RH and then back to 50%. Six different testing profiles were used (see Table 2). The profiles represent an extreme and relatively sudden change, which may be a worst-case scenario for library and archive materials. A representative sample of each single sheet material was placed on the balance and imaged with a DSLR camera on the time-lapse function for each run of the test in order to compare weight change with strain.

Part 2 Profiles

Absorption 1	50%-70% RH	2-hour RH change, 5 days constant RH
Absorption 2	30%-50% RH	2-hour RH change, 5 days constant RH
Desorption 1	70%-50% RH	2-hour RH change, 5 days constant RH
Desorption 2	50%-30% RH	2-hour RH change, 5 days constant RH

Table 1: Part 2 testing profiles. Each profile had a 2-hour change in RH from the initial set point to a new set point and held the new RH for a five 5-day period.

Part 3 Profiles

Absorption 1	50%-60%-50% RH	2-hour RH change, 12-hour constant RH
Absorption 2	50%-70%-50% RH	2-hour RH change, 12-hour constant RH
Desorption 1	50%-30%-50% RH	2-hour RH change, 12-hour constant RH
Desorption 2	50%-20%-50% RH	2-hour RH change, 12-hour constant RH
Desorption 3	50%-10%-50% RH	3-hour RH change, 12-hour constant RH
Oscillating	50%-70%-50%-30%-50%-70%-30%-70%-50% RH	2-hour RH change, 12-hour constant RH

Table 2: Part 3 testing profiles. Each profile began with a 12-hour period of constant RH at 50%, then changed to the next set point over a period of 2 or 3 hours, remained at that set point for 12-hours, and then returned to 50% RH over a 2-hour period and remained at 50% for 12 hours.

Analysis of data from parts 2 and 3 shed light on the relationship between changes in RH, moisture content, and mechanical behavior resulting in four major observations. As with most research, these observations have led to more research questions.

First, all objects tested responded very quickly to changes in RH. Most single sheets lagging behind the change in RH by only minutes and most books by a few hours. The change in strain slowed as moisture diffusion slowed and finally the strain plateaued when moisture equilibration had been reached (see Figure 1). Strain data showed that most single sheet samples reached equilibration within about twelve hours in moderate RH ranges between 30% and 70%. It should be noted that no book samples reached equilibration within the twelve-hour test period, however the final period at 50% RH was extended to seventeen hours and many samples had reached near equilibration within that time period.

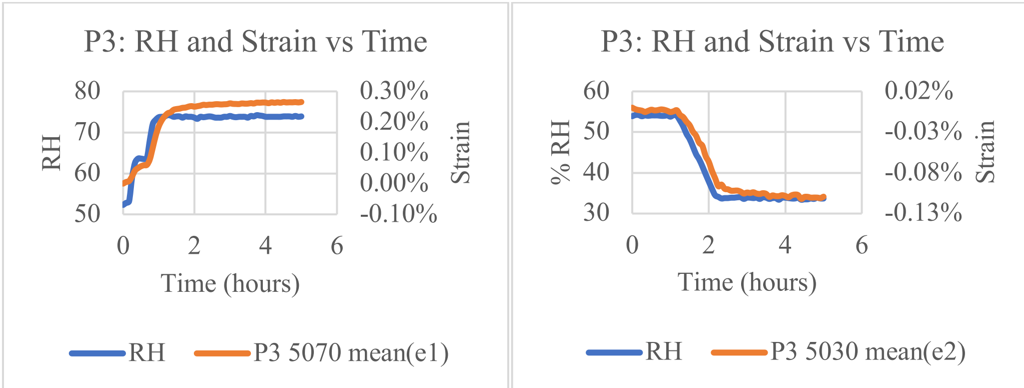


Figure 1: Mean primary strain and RH vs time, selected absorption and desorption profiles. The increase or decrease in strain occurs very quickly as the RH increases or decreases. These graphs show the first five hours of the absorption tests on the left and desorption tests on the right for paper sample P3. The blue line shows the change in RH and the orange the change in strain. The change in strain lags behind by only minutes. Most single sheet samples responded as quickly as this example.

The second observation was the most consistent among all objects tested. With each 10% change in RH, the strain doubled or nearly doubled within the RH ranges tested from 10% to 70%. Figure 2 shows the peak strain of representative samples at each RH set point in Part 3.

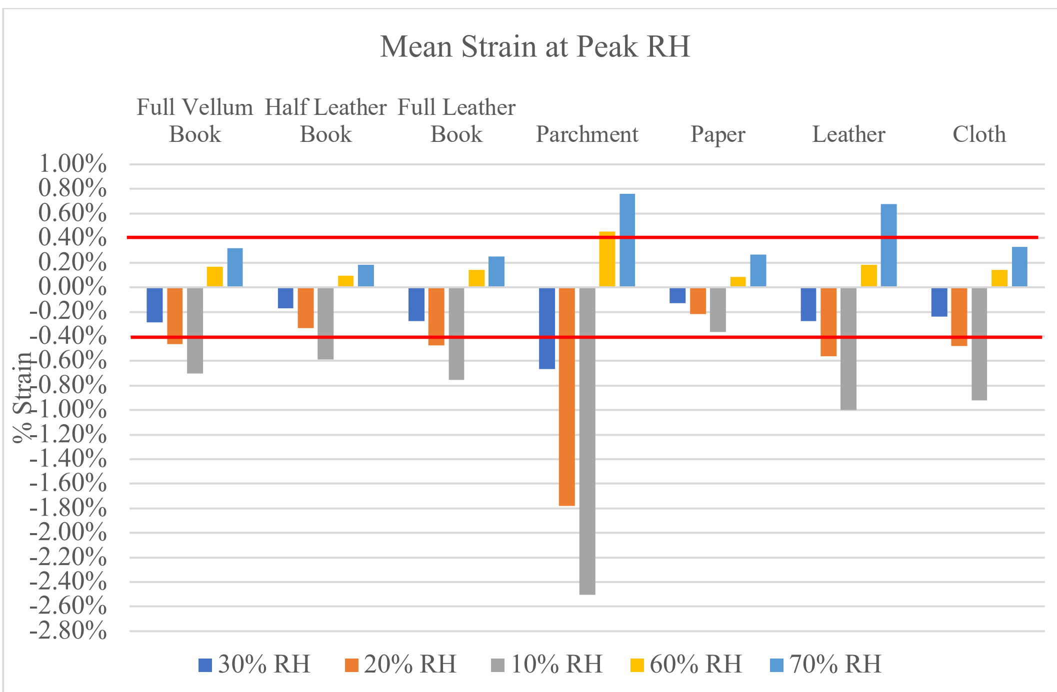
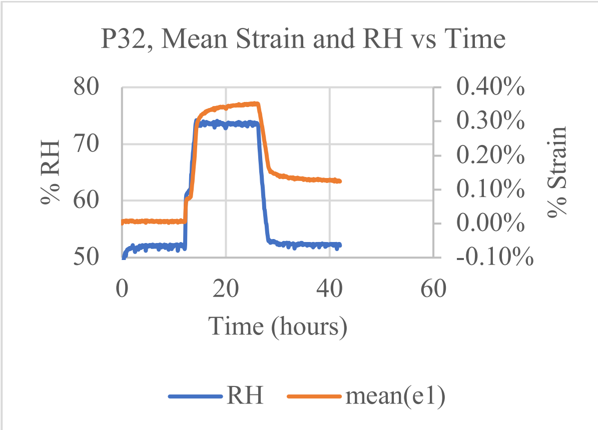


Figure 2: Peak strain of a selection of samples for each test profile. In most samples, the strain nearly doubled with each 10% increase or decrease in RH within the ranges tested. Parchment and vellum bound books experienced the greatest degree of expansion and contraction. The red lines indicate the yield point determined by MCI scientists.

Overall, parchment single sheets and vellum bound books were the most responsive materials, as expected. With a 20% change in RH, all the parchment samples tested exceeded 0.4% strain or -0.4% strain. Positive strain values indicate object expansion while negative strain values indicate object contraction. The Smithsonian Museum Conservation Institute (MCI) determined that the yield point of most organic materials occurs at 0.4% strain, particularly if the material is restrained (Tumosa et al., 1996). Based on the MCI findings, if restrained, the parchment samples tested would likely experience some mechanical damage with a 20% change in RH even within moderate ranges. The strain levels experienced by many parchment and paper samples with a change from 70% to 50% RH in each testing profile suggests that, in agreement with current recommendations, 70% RH is too high for single sheet cellulosic and collagen materials as mechanical deformation may occur.

Some vellum and leather bound books did reach -0.4% stain at 20% and 10% RH, however no visual damage occurred and no apparent damage can be seen in the data as all samples returned to or near the initial 0% strain. Investigating the effects of low RH was of particular interest. Nearly all objects tested did return to or near the initial 0% strain at the end of each desorption test in part 3 showing no permanent damage. It is possible damage may occur given longer periods at a constant RH. It is also possible these books have what is known as strain hardening—they have already experienced excessive dampness and dryness during their lifetime and been stretched beyond their initial yield point resulting in having a new, higher yield point. As a result, they will not likely experience more damage under these conditions and the MCI 0.4% strain yield point does not apply.

The third observation was that all samples exhibited hysteresis in the absorption tests. Absorption hysteresis is a phenomenon in which the absorbed quantity of gas, in this instance water vapor, differs in organic materials depending on whether it is being added or removed. Typically, the material has more water at a given RH during desorption then during absorption. DIC data showed in each absorption test when the RH returned to 50% the strain decreased quickly, but no sample returned to the initial 0% mean primary strain within the final twelve-hour period of constant RH. All samples had some residual strain which varied within each type of material, but most samples had about 30% excess residual strain. To establish this behavior was the result of hysteresis, further tests were conducted using three methods of measurement: DIC, an electronic moisture meter, and an analytical balance. When the DIC strain data for each sample was plotted as percent strain vs RH, it had the typical appearance of a hysteresis loop (see Figure 3). The balance data showed the samples gained and lost weight at nearly the same rate as the increase or decrease in strain and the samples did not return to their initial weight indicating there is likely still moisture present. Readings from the electronic moisture meter showed samples had a higher moisture content at the end of absorption tests than they did at the beginning, which correlates with strain values.



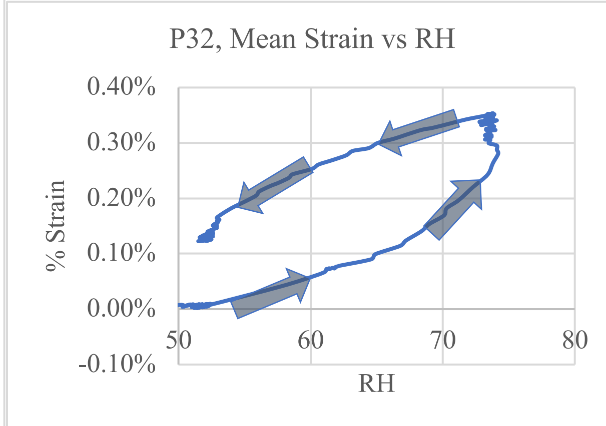


Figure 3: On the left, paper sample P32 strain and RH vs time. The paper does not return to 0% strain during the final 12-hour period at a constant RH. The same data is graphed on the right as strain vs RH. It has the typical appearance of a hysteresis loop. Absorption hysteresis is a phenomenon in which the adsorbed quantity of gas, in this instance water vapor, differs in organic materials depending if it is being added or removed. Typically, there is more water vapor in the material during desorption.

While these tests demonstrate there is a correlation between strain and changes in moisture content, the samples with the greatest moisture content did not necessarily experience the greatest strain. The magnitude of change experienced by any individual sample is due to a combination of characteristics, such as sample thickness, porosity, paper fiber content, sizing type, and sample density. Furthermore, the effects of hysteresis created difficulty in determining if permanent damage had occurred. The residual moisture responsible for the elevated end strain may be driven off over time or an increase in temperature. More research is needed.

The final observation refers only to single sheets of paper and parchment. When these materials lost moisture due to a decrease in RH, whether in the absorption or desorption tests, most paper and all parchment samples curled. With absorption tests samples retained curl when the RH returned to 50% with curl being more severe after having experienced 70% RH. Curl was evident in the DIC data as well as with visual observations; data showed the residual positive strain in the primary direction and negative strain in the secondary direction indicating samples contracted in the secondary direction (see Figure 4). The parchment samples curled the most severely and also show the most negative secondary strain. It is inconclusive if this change is permanent or not. A collection object would require intervention from a conservator to humidify and flatten the object. With the desorption tests, particularly in regards to very low RH, many parchment samples curled so severely the speckle pattern was obscured and complete data was not collected. All samples did relax and return to their initial shape in both directions during the final period at a constant 50% RH and near the initial 0% strain.

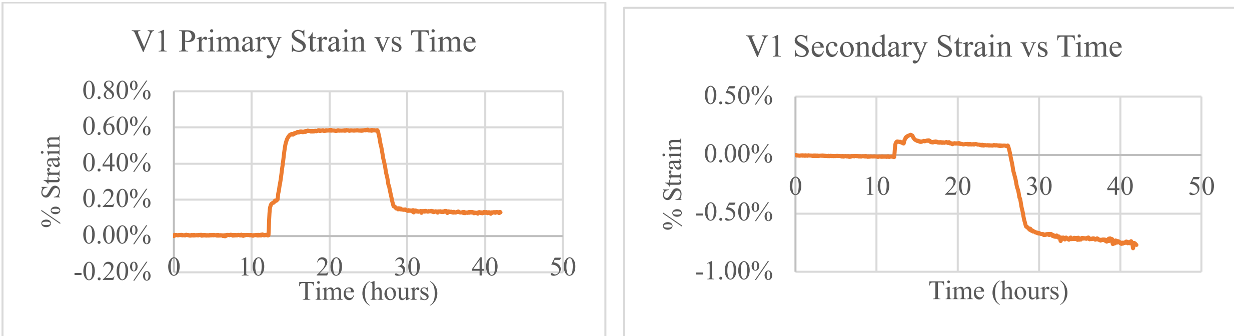


Figure 4: Mean primary strain (left) and mean secondary strain (right) vs time for parchment sample V1 during profile 50%-70%-50%. On the left, the sample shows positive strain in the primary direction at the end of the final period at a constant 50% RH. In the secondary strain direction, on the right, the sample contracts resulting in negative strain at the end of the final period at 50% RH. This is visually observed as curl.

Within the framework of this study four major observation were made and some new questions arose. 1) Hygroscopic materials physically respond very quickly to a change in RH. In previous research conducted by IPI discussed at the beginning of the paper, it was found that museum cases and portfolio boxes slow down moisture diffusion so that paper-based collections do not feel the full extent of short-term RH changes. In these storage containers, the most vulnerable object on the top of the stack may be more protected. Books that are particularly sensitive to RH changes may also be protected with a simple paper wrapper or be placed in a box to slow down moisture diffusion. 2) With each 10% change in RH the strain doubled or nearly doubled within the RH ranges tested from 10% to 70%. At a constant temperature it can be predicted that most paper-based collection materials will follow this general rule, which can serve as a guideline for future modeling of mechanical behavior. 3) Materials that experienced moisture absorption did not return to their original state due to hysteresis. 4) Single sheets of paper and parchment curled with desorption. Samples retained curl after having experienced an increase in RH.

Hysteresis and curl need to be further studied. Cycling in which the RH increases and returns many times may result in damage and may exacerbate the effects of hysteresis resulting in damage. Furthermore, in this project, materials experienced a single, rapid change in RH and did not experience permanent deformation. Earlier tensile tests of film-based materials conducted by IPI showed a slow application of weight, or load, caused more damage than a fast application of load. With a slow application of load the plastic film rearranges at the molecular level resulting in permanent deformation. The risks of fast verses slow change in RH resulting in hygric strain for paper-based library and archive materials is not documented and needs to be further researched.

IPI is currently investigating the extent to which temperature impacts moisture content of collection materials. This temperature induced change happens much faster than changes in moisture content due to changes in RH. Using DIC, it would be possible to evaluate the physical impact on collections due to temperature changes. A scenario in which objects often experience rapid changes in temperature as well as RH is during access; storage temperatures tend to be cooler than use spaces, such as study rooms. Ultimately, it may be possible to design guidelines for related storage and use environmental conditions to minimize the impact on objects as they make environmental transitions throughout an institution.

This project has pioneered the use of DIC for understanding the dynamic relationship between relative humidity, moisture content, and the physical response of collection materials. Further research using DIC will ultimately allow us to fully characterize the physical response of library and archive materials to changes in RH and temperature and establish more accurate recommendations for storage and use environments.

References

Bigourdan, Jean-Louis. 2017. Executive Summary – NEH Grant #PR-50087-10. *Methodologies for Sustainable HVAC Operation in Collection Environments.*

Popescu, Carmen-Mihaela, Callum A.S. Hill, Craig Kennedy. 2016. Variation in the Sorption Properties of Historic Parchment Evaluated by Dynamic Water Vapor Sorption. *Journal of Cultural Heritage*: 17: 87-94.

Tumosa, C. S., M. F. Mecklenburg, D. E., and M. McCormick-Goodhart. 1996. A Discussion of Research on the Effects of Temperature and Relative Humidity on Museum Objects. *Western Association for Art Conservation*, 18: 19-20.